

Accelerating Plasma Mirrors to Investigate Black Hole Information Loss Paradox

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The question of whether Hawking evaporation violates unitarity, and therefore results in the loss of information, remains unresolved since Hawking's seminal discovery. So far the investigations remain mostly theoretical since it is almost impossible to settle this paradox through direct astrophysical black hole observations. Here we point out that relativistic plasma mirrors can be accelerated drastically and stopped abruptly by impinging ultra intense x-ray pulses on solid plasma targets with a density gradient. This is analogous to the late time evolution of black hole Hawking evaporation. A conception of such an experiment is proposed and a self-consistent set of physical parameters is presented. Critical issues such as black hole unitarity may be addressed through the measurement of the entanglement between the Hawking radiation and their partner modes.

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The question of whether Hawking evaporation [1] violates unitarity, and therefore results in the loss of information [2], remains unresolved since Hawking's seminal discovery. Proposed solutions range from black hole complementarity [3] to firewalls [4, 5] (see, for example, [6, 7] for a recent review and [8] for a counter argument). So far the investigations remain mostly theoretical since it is almost impossible to settle this paradox through direct astrophysical observations, as typical stellar size black holes are cold and young. Here we point out that the Hawking evaporation at its late stage can be mimicked by accelerating plasma mirrors based on state-of-the-art laser and nano-fabrication technologies. We show that a relativistic plasma mirror [9–11] induced by an intense x-ray beam traversing a solid plasma target with an increasing density and a sharp termination can be accelerated drastically and stopped abruptly. Critical issues such as how the black hole unitarity would be preserved can in principle be addressed.

There have been proposals for laboratory investigations of the Hawking effect, including sound waves in moving fluids [12], electromagnetic waveguides [13], traveling index of refraction in media [14], Bose-Einstein condensates [15], and electrons accelerated by intense lasers [16]. However, most of these are limited to verifying the thermal nature of the Hawking radiation. It has long been recognized that accelerating mirrors can mimic black holes and emit Hawking-like thermal radiation [17]. That accelerating mirrors can also address the informa-

tion loss paradox was first suggested by Wilczek [18].

As is well-known, the notion of black hole information loss is closely associated with quantum entanglement. In order to preserve the “black hole unitarity”, Wilczek argued, based on the moving mirror model, that the partner modes of the Hawking particles would be trapped by the horizon until the end of the evaporation, where they would be released and the black hole initial pure state recovered with essentially zero cost of energy. More recently, Hotta et al. [19] confirmed that the released partner modes are simply indistinguishable from the zero-point vacuum fluctuations. On the other hand, there is also the notion that these partner modes would be released in a burst of energy, for example, in the Bardeen model [20]. It is even more important to determine how the black hole information is retrieved. Does it follow the Page curve [21], or some alternative scenario [22]? This would critically impact on various conjectures such as firewalls that assume certain scenario for the entanglement entropy. The observation of either a burst of radiation or zero-point fluctuations, and the measurement of the entanglement between these modes and the Hawking particles and its evolution, should help to shed much lights on the black hole information loss paradox.

Plasma wakefield acceleration for high energy particles driven by lasers [23] or particle beams [24] has been a subject of worldwide pursuit. In the nonlinear regime of plasma perturbations, the plasma wakefield will undergo “wave-breaking” that results in a huge pileup of density perturbation, like a tsunami. It has been proposed that this feature can provide yet another salient utility, a highly relativistic plasma mirror, that can reflect and Lorentz-boost a witness optical laser pulse to turn it into an even more compressed x-ray beam [9–11].

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By the conservation of energy, the driving laser pulse must lose its energy by exciting the wakefield. Since the photon number is nearly conserved in such system, the energy loss is manifested by the frequency redshift, which causes the slow-down of the laser [25–27]. To counter this *natural* tendency of deceleration, one can envision an *artificial* inducement of acceleration of the laser by traversing a plasma with increasing density. Such accelerating mirror plays the role of the black hole center, while the mirror’s asymptotic null ray serves as the equivalent horizon. Additionally, terminating the plasma target sharply would result in a sudden stoppage of the mirror motion, which would mimic the end-life of black hole [18], independent of whether it would evaporate entirely or end with a Planck-size remnant [7, 28].

In the adiabatic limit, the laser-plasma interaction can be described in the comoving coordinates $\chi \equiv x - v_g t$ and $\tau = t$ by the following nonlinear coupled equations:

$$\left[\frac{2}{c} \frac{\partial}{\partial \chi} - \frac{1}{c^2} \frac{\partial}{\partial \tau} \right] \frac{\partial a}{\partial \tau} = k_{p0}^2 \frac{a}{1 + \phi}, \quad (1)$$

$$\frac{\partial^2 \phi}{\partial \chi^2} = -\frac{k_{p0}^2}{2} \left[1 - \frac{(1 + a)^2}{(1 + \phi)^2} \right], \quad (2)$$

where ϕ and a are the (normalized dimensionless) scalar and vector potentials of the laser, and $k_{p0} = \omega_{p0}/c = \sqrt{4\pi r_e n_{p0}}$. Here $r_e = e^2/mc^2$ is the classical electron radius, n_{p0} is the ambient uniform plasma density. According to the *principle of wakefield*, the phase velocity of the plasma wakefield equals the group velocity of the driving laser or particle beam. For uniform plasmas, $v_{ph0} = v_{g0} = \eta_0 c$, where the refractive index $\eta_0 = \sqrt{1 - (\omega_{p0}^2/\omega^2)/(1 + \phi)} \leq 1$. In the nonlinear regime, where the laser strength parameter $a_{L0} > 1$, the density perturbation approaches a delta function, but periodic nonetheless. As discussed above, the laser loses its energy through frequency redshift [26, 27]:

$$\frac{\partial \omega}{\partial \chi} = -\frac{\omega_{p0}^2}{2\omega} \frac{\partial}{\partial \chi} \left(\frac{1}{1 + \phi} \right). \quad (3)$$

As the frequency decreases, η_0 decreases as well, and so the laser slows down as it traverses the plasma.

Now we model the laser intensity variation along the pulse as a sine function [25]:

$$a_L(\chi) = \begin{cases} a_{L0} \sin(\pi\chi/L), & -L < \chi \leq 0, \\ 0, & \text{otherwise,} \end{cases} \quad (4)$$

Under the assumption that $\phi \ll 1$, which is satisfied even if $a_{L0} > 1$ as long as $L \ll \lambda_p$ [25], the solution to Eq.(2) for the “slowly varying part” of the scalar potential is

$$\phi \simeq \frac{a_{L0}^2 k_{p0}^2}{8} \left\{ \chi^2 - 2 \left(\frac{L}{2\pi} \right)^2 \left[1 - \cos(2\pi\chi/L) \right] \right\}. \quad (5)$$

The variation of ϕ along the laser pulse is then

$$\frac{\partial \phi}{\partial \chi} \simeq \frac{a_{L0}^2 k_{p0}^2}{4} \left[\chi - \frac{L}{\pi} \sin \left(\frac{2\pi\chi}{L} \right) \right], \quad -L \leq \chi \leq 0. \quad (6)$$

We see that $\partial\phi/\partial\chi$ is negative definite. Therefore, $\partial\omega/\partial\chi$, as defined in Eq.(3), is also negative definite.

The plasma dispersion relation and phase velocity under nonuniform density have been investigated and confirmed through computer simulations by Lobet et al. [29]. By definition, the eikonal of the plasma wave, $\theta(x, t)$, satisfies the relationships $\omega_p = -\partial\theta/\partial t$ and $k_p = \partial\theta/\partial x$, and has the cross differentiation property $\partial^2\theta/\partial t\partial x = \partial^2\theta/\partial x\partial t$. As a consequence, we have

$$\frac{\partial k_p}{\partial t} = -\frac{\partial \omega_p}{\partial x}. \quad (7)$$

As plasma oscillations are a collective effect, the minimum length scale for the response to density variation is the plasma wavelength, λ_p . Let the characteristic length of the density variation be D . If $\lambda_p \ll D$, then the wave number $k_p(x_1)$ at location x_1 can be related to that at x_0 through the Taylor expansion: $k_{p1} = k_{p0} + (\partial k_p/\partial t)\Delta t = k_{p0} - (\partial \omega_p/\partial x)\Delta t$, where $\Delta t = t_1 - t_0 \ll D/c$. Substituting it in the phase velocity at x_1 : $v_{ph1} = \omega_p(x_1)/k_p(x_1)$, we then arrive at

$$v_{ph1} = \frac{\omega_p}{k_{p0} - (\partial \omega_p/\partial x)\Delta t} \simeq v_{ph0} \left(1 + \frac{\partial \omega_p}{\partial x} \frac{\Delta t}{k_{p0}} \right). \quad (8)$$

Repeating this argument for N times, $(t_2 - t_1), \dots, (t_N - t_{N-1})$, combining them iteratively and ignoring all quadratic and higher order terms, one eventually arrives at an expression based on the global time t :

$$v_{ph}(t) \simeq v_{ph0} \left(1 + \frac{\partial \omega_p}{\partial x} \frac{t}{k_{p0}} \right), \quad \lambda_p \ll D. \quad (9)$$

Here we set $t_0 = 0$. We see that if $\partial \omega_p/\partial x > 0$, then the velocity of the plasma mirror, $v_M \equiv v_{ph}$, would increase in time. Invoking the wakefield principle for uniform plasmas, we find

$$v_M \simeq c \sqrt{1 - \frac{\omega_{p0}^2}{\omega^2} \frac{1}{1 + \phi}} \left(1 + \frac{\partial \omega_p}{\partial x} \frac{t}{k_{p0}} \right). \quad (10)$$

Since $d/dt = \partial/\partial t + v_g \partial/\partial x$, the acceleration of the plasma mirror is

$$\begin{aligned} \ddot{x}_M = & \frac{c}{2\eta_0} \left[v_g \left(1 + \frac{\omega_{p0}^2}{\omega^2} \right) \frac{\omega_{p0}^2}{\omega^2} \frac{\partial}{\partial x} \frac{1}{1 + \phi} \right] \left(1 + \frac{\partial \omega_p}{\partial x} \frac{t}{k_{p0}} \right) \\ & + c\eta_0 \left(\frac{\partial \omega_p}{\partial x} \frac{1}{k_{p0}} + \frac{\partial^2 \omega_p}{\partial x^2} \frac{v_g t}{k_{p0}} \right). \end{aligned} \quad (11)$$

The first term corresponds to the natural deceleration while the second term the artificial acceleration. As a prerequisite for laser propagation in a plasma, $\omega_p^2/\omega^2 \ll 1$. Under appropriate choice of parameters, the gradient induced acceleration can in general dominate over the natural deceleration. From here on we will ignore the first term and retain the artificial acceleration term only.

Let the plasma target thickness be X , and the density gradient be

$$n_p(x) = \begin{cases} n_{p0} e^{x/D}, & 0 \leq x \leq X, \\ 0, & \text{otherwise,} \end{cases} \quad (12)$$

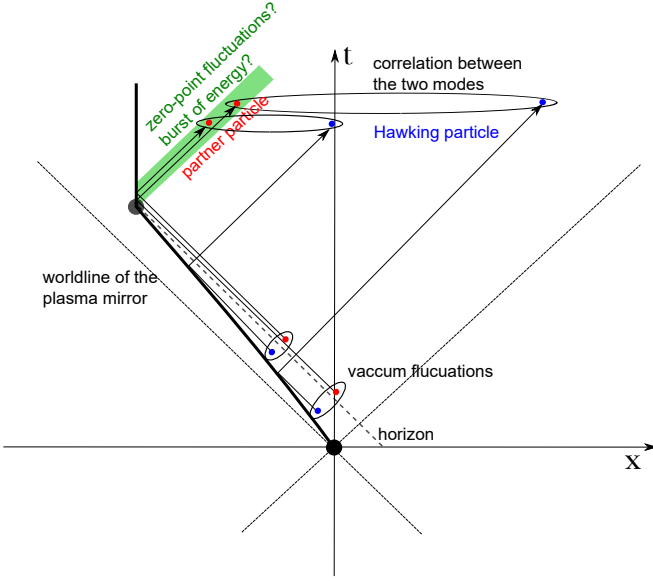


FIG. 1: The worldline of an accelerating relativistic plasma mirror and its relation with vacuum fluctuations around the horizon. In particular, the entanglement between the Hawking particles (blue) emitted at early times and their partner particles (red) collected at late times is illustrated. The green strip represents either a burst of energy or zero-point fluctuations emitted when the acceleration stops abruptly.

where n_{p0} is the initial plasma density at $x = 0$. Then we have

$$\ddot{x}_M \simeq \eta_0 c^2 \left[\frac{1}{2D} + \frac{x}{4D^2} \right] e^{x/2D}, \quad 0 \leq x \leq X, \quad (13)$$

where we have approximated $v_g t \approx x$. The corresponding analog Hawking temperature [30] is then

$$k_B T_H(x) = \frac{\hbar \ddot{x}_M}{2\pi c} = \frac{c\hbar}{2\pi} \eta_0 \left[\frac{1}{2D} + \frac{x}{4D^2} \right] e^{x/2D}. \quad (14)$$

Figure 1 shows the worldline of the accelerating plasma mirror and the spacetime evolution of the entangled vacuum fluctuating pairs. The partner modes of the Hawking particles are temporarily trapped by the horizon and would presumably be released when the mirror stops abruptly. Depending on different theories, there would be either a burst of real particles, or zero-point vacuum fluctuations [18, 19]. The energies of the photons of the burst, if exists, should be comparable to that of the Hawking particles, as they are entangled pairs. Through the measurement of the two-point correlation function between the Hawking particles and either the burst of energy or zero-point fluctuations, the entanglement entropy of the system as a function of time can be deduced.

Figure 2 is a schematic diagram for our proposed experiment. In our conception, a driver pulse from an optical laser traverses the 1st (gaseous and uniform) plasma target, which creates a relativistic plasma mirror with a concave transverse density distribution. A source pulse, prepared by the same laser, is reflected by the plasma

mirror with frequency increased by a factor $4\gamma^2$, where γ is the Lorentz factor of the mirror. This x-ray pulse will pass through a Bragg diffraction crystal to arrive at the 2nd plasma target, which is solid with graded density, presumably fabricated via nano-technology. The driver pulse, on the other hand, can be diffracted to a different path.

This second plasma mirror accelerates due to the density gradient and emits analog Hawking radiation, which propagates in the backward direction. Note that the frequencies of the Hawking photons tend to be sufficiently lower than the plasma frequencies of the solid target (see the numerical example below). A naive consideration based on plasma physics may conclude that the Hawking photons cannot traverse the target. It is fortuitous that in the nonlinear regime of plasma perturbations, all free electrons in the wake of an intense pulse would be evacuated, resulting in a channel with a much lower effective plasma frequency, through which the Hawking photons can propagate. At the time when the mirror arrives at the back-end, it stops abruptly. At this point all the partner modes would be suddenly released and travel backwards. Upstream of the 2nd target, the supposed zero-point fluctuations will be measured by condensers and amplifiers, while the Hawking and the partner particles (if real), which are lower in energy than that of the x-ray pulse, will be Bragg diffracted to a time-resolved photo-sensor. The time resolution should be much finer than the penetration time, say femtosecond, such that the final burst of partner particles can be distinguished from the Hawking photons.

As a numerical example, let us consider a 10 PetaWatt single-cycle green laser to produce the x-ray pulse. A minor fraction of this power is used for the driver pulse that impinges the 1st target, which, by design, induces a concave, constant velocity relativistic plasma mirror with the Lorentz factor $\gamma = \omega_d/\omega_p \sim 10$. The source pulse carries essentially 10 PW, with 5×10^{19} photons per pulse, counter-propagates to collide with the mirror. After reflection, it is Lorentz boosted to $\hbar\omega_x = 4\gamma^2\omega_s \sim 1\text{keV}$. This corresponds to a wavelength $\lambda_x \sim 1.2\text{nm}$. Assume the reflectivity of the 1st mirror is $Y = 10^{-5}$ [31]. Then the number of photons in the x-ray pulse is $N_x = 5 \times 10^{14}$. Let the depth of focus of the x-ray be much larger than the 2nd target thickness X so as to maintain a near-constant pulse radius $R \sim 330\lambda_x \sim 400\text{nm}$. Then the x-ray strength parameter is $a_x = eE/mc\omega_x \sim 2 > 1$, which is sufficient to excite nonlinear plasma wakefields for the accelerating mirror.

There are four key length parameters in our proposed experiment, which, due to various constraints, follow the inequality: $\lambda_x \ll \lambda_p(x) \ll D \ll X$. Let the initial plasma density be $n_{p0} = 1 \times 10^{21}\text{cm}^{-3}$. This corresponds to $\lambda_{p0} = 1000\text{nm}$. Matching it, we assume $D = \lambda_{p0}$ and let $X = 10D$. Although the requirement that $\lambda_p(x) \ll D$ is not quite satisfied initially, the exponential increase of the plasma density guarantees that it will soon be the case throughout most of the target. At the back-end of

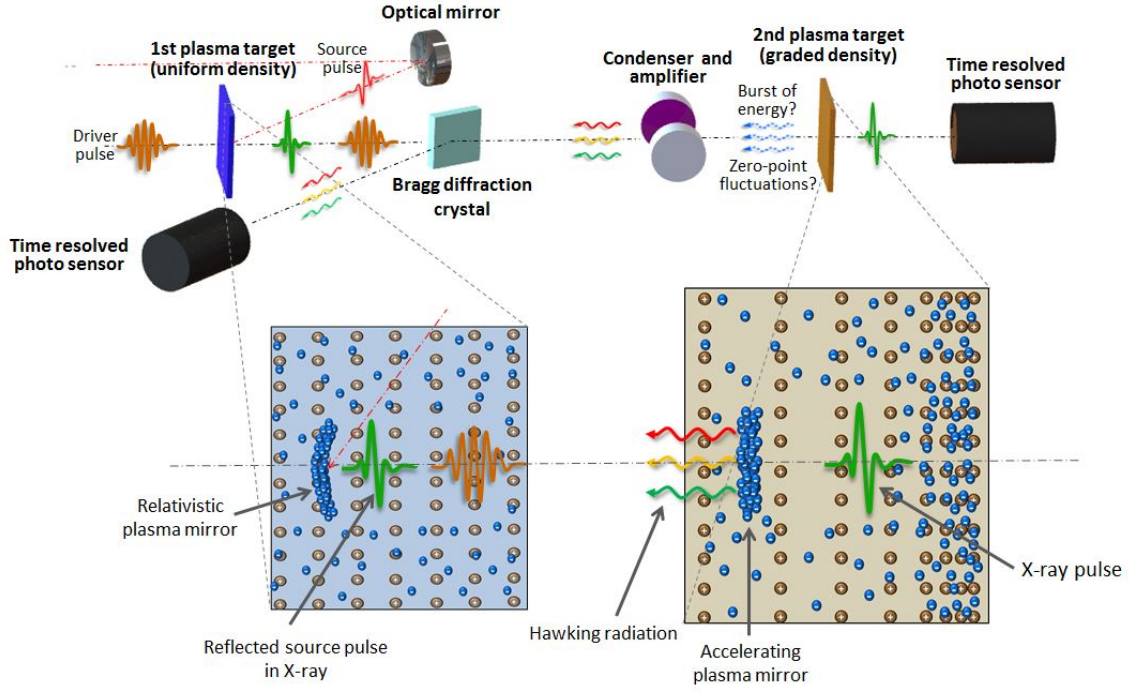


FIG. 2: A schematic diagram of the proposed analog black hole experiment. The first, gaseous and uniform plasma target is used to prepare a high intensity x-ray pulse. The x-ray pulse will induce an accelerating plasma mirror due to the increasing plasma density in the second target. As the mirror stops abruptly, it will release either a burst of energy or zero-point fluctuations. The correlation function between either of these signals and the Hawking photons is measured downstream.

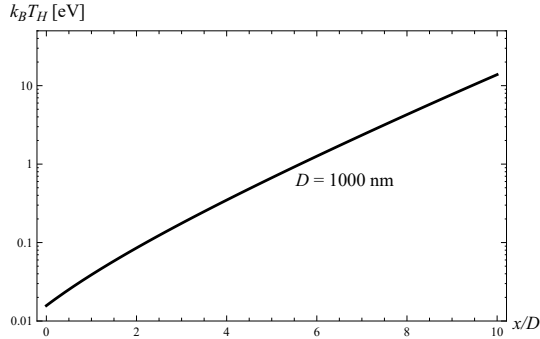


FIG. 3: The analog Hawking temperature as a function of the penetration depth, x , of the accelerating plasma mirror, normalized by the characteristic length of the plasma density gradient D . Here we assume $D = 1000\text{nm}$ and $X = 10D$.

the target, the density reaches $n_{pf} \sim 2 \times 10^{25}\text{cm}^{-3}$. Figure 3 shows the Hawking temperature as a function of the penetration depth, where it increases exponentially from 0.02 to 13.8 eV. Limited by the size of the mirror, $2R_x \sim 800\text{nm}$, the Hawking spectrum below 1.8 eV would be cutoff. Note that although the (2nd) plasma mirror is not a perfect reflector, the spectrum of the Hawking and partner signals should remain unaltered since the reflection is microscopically stochastic.

For this experiment to render meaningful result, the Hawking signals must compete successfully against var-

ious inevitable background photons at comparable energies. We assume that the experiment is performed in a high vacuum and low temperature environment. Then the only potential background would be x-ray triggered Compton scattering, which has a finite (but minute) partial cross section in the backward direction. One salient feature of our experiment in terms of the signal-to-noise ratio is that the Hawking and partner signals travel in the backward direction, whereas most x-ray induced background particles would move in the forward direction. Dictated by the kinematics for a “low” energy initial photon (in our case at $1\text{keV} \ll mc^2$), the back-scattered photon energy is essentially unchanged. As the Bragg diffraction crystal is designed to allow the passage of the keV photons while diffracts those at 1-10 eV, the signals and the Compton photons would be diverted to separate paths. We conclude that the background in this experiment should be minute.

Moving mirrors can provide additional utilities for investigating black hole physics. As was pointed out by Wilczek [18], a rapidly receding mirror has a dynamical effect that mimics the redshift due to the spacetime distortion near the surface of the black hole. In addition, having a finite mass, the plasma mirror should recoil upon thermal emissions, which would presumably provide a model for the intrinsic black hole entropy [18].

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